

Planar Textile Antenna for Body Centric Wireless Communication System

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Abstract—One of the most important aspects for body centric communication is the development of the textile antenna for on-body communication. Antennas for on-body environment usually suffer performance degradation caused by the human body. Apart from that, textile antenna gets easily bent, flexed, wrinkled or wet. This paper presents an investigation on three different designs and types of planar antennas, which are single band textile dipole antenna, fractal Koch multiband dipole antenna and monopole ultra wide band antennas. The performance of the antennas has been evaluated in terms of bending, wetness condition and on-body simulation. The results show that the bending effect is not critical in free space for the planar antennas, but the performance is notably degraded under wet condition while the antenna reflection coefficient is shifted when placed on the human body.

1. INTRODUCTION

Body centric wireless communication is the subject area combining Wireless Body Area Network (WBANs), Wireless Sensor Network (WSNs) and Wireless Personal Area Network (WPANs). The need of such body centric communication in today's society is evident based on its wide range of wearable applications including healthcare, lifestyle, protection, monitoring and safety [1, 2]. Types of communications within the body area networks can be divided into three categories, namely off-body communications involving off-body to on-body device or system, on-body communications involving on body networks and wearable system and in-body communication involving the communications between medical implants and sensor networks [3]. Even though security and privacy issues arise with the implementation of this type of communication, its importance can be observed by the rising number of related research conducted over the years.

The wearable system made from 100% fabric material has attracted a lot of attention among researchers. This novel technology is known as “smart clothing”, which generally consists of a microcontroller, sensors, energy source, radio frequency devices including antenna, transmitter and receiver. The smart clothing will be very beneficial in various monitoring activities such as user detection, location tracking and real-time health monitoring [4]. For example, VTAMN shirt is integrated with biosensor and bio actuator such as ECG reading [5], temperature and fall detection for tele-assistance in medicine, WEALTHY is developed with intelligent monitoring during task and physical exercise [6] and LIFE SHIRT is equipped with recording psychical parameter such as electrocardiogram, ribcage, body posture and body oxygen saturation [7]. The wearable system can also be used for children tracking, exercise and diet progress monitoring, or tracking the army's location and condition. Recently, textile sensors using nano-electric polymer have been developed to monitor truck motion for rehabilitation harmful activities [8].

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For on-body communication, choosing a suitable type of antenna is very crucial as antenna performance consequently affects the efficiency of a system. On the other hand, it is also vital for the antenna to have a performance that supports the electromagnetic signal propagation close to the body. The wearable antennas using textile material such as denim [9–11], felt [12] and foam fabric [13] have been mostly implemented on body centric communication due to the flexibility and robustness to be equipped on textiles that can be worn as part of clothing. On top of that, textile antennas are also cheap, light, and can operate in a wide range of frequencies. For example, the fully Ultra Wideband (UWB) all-textile is designed using felt fabric in WBAN application [14], 2.45 and 5.2 GHz Sierpinski inverted-F antenna is designed using polyester fleece substrate for various future 802.15 wireless standard [15] and 2.45 GHz dual polarized patch antenna is designed using flexible protective foam with fully integration into protective garment [16].

In designing wearable antennas, their features such as stability of performance, and flexibility and durability of the materials are important to be tested beforehand. Textile antenna is a suitable candidate for wearable application since this antenna is capable to give comfort to users. However, the bending effect of the antenna towards different body placement may consequently change the physical structure of the antenna. Hence, affecting the antenna resonance frequency is existed. In addition, it is also very important to consider wetness aspect in designing textile antennas. The high dielectric constant of water could alter the antenna properties, subsequently affecting its overall performance. From the previous research, 2.45 GHz antenna needs less than 3% of water absorption to ensure a stable antenna performance [17]. This paper discusses the performance of three planar antennas with a human body in close proximity. The bending and wetness conditions are also considered and further discussed in this paper.

2. TYPES OF PLANAR TEXTILE ANTENNA

Single band, UWB band and multiband antennas have been designed using denim material as substrates and ShieldIt fabric as conducting elements as shown in Fig. 1. Firstly, a single band dipole antenna is designed with $L = 25.5$ mm and $w = 4$ mm; operating at 2.45 GHz. A CPW-fed UWB antenna is designed to operate between 2 and 13 GHz with the dimension of radius, $rad_a = 20$ mm, $rad_b = 25$ mm, $h = 66$ mm and $l = 40$ mm [18]. Then, the Koch-fractal multiband antenna is designed with dipole structures operating at 0.9, 2.5 and 5.8 GHz [19] with respective dimension, $l_1 = 54.9$ mm, $l_2 = 24.45$ mm, $l_3 = 7.05$ mm and $w = 3$ mm. The permittivity of denim fabric is found to be 1.67 with tangent loss of 0.025. The electrical properties of denim were examined by using open ended coaxial probe method. The thickness of the denim substrate is 0.85 mm. The ShieldIt fabric is introduced as conductive element which consists of a rugged rip-stop polyester substrate, conductive nickel and copper plated with a non-conductive hot melt adhesive on its reverse side. The ShieldIt fabric characterized as hydrophobic, reduce moisture absorption and allow maintain conservation its electromagnetic properties [20].

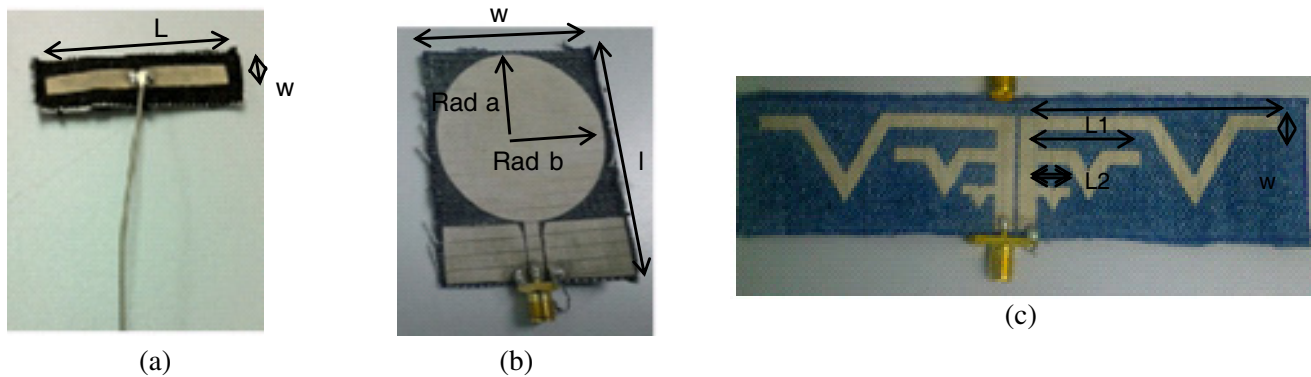


Figure 1. Planar textile antenna using denim material. (a) Single band dipole antenna. (b) CPW UWB antenna. (c) Koch fractal multi-band antenna.

3. RESULTS AND DISCUSSIONS

The textile antennas are evaluated toward different placements on human body, bending, and wetness experiment. From the previous research, degradation of resonant frequency of 2.45 GHz cotton antenna performance has been reported under the bending condition due to change of the physical antenna structure [21]. This is caused by the electromagnetic (EM) coupling effect from the human body influence the antenna performance such as input impedance, power efficiency, resonant frequency and bandwidth [22]. Furthermore, the antenna placement on the body needed to be study including the forearm, arm, chest, and backside to find the placement which is able to maintain the antenna performance. Then, the textile antenna is also needed to be investigated under wet condition to evaluate antenna performance with the presence of water. The water has high dielectric constant could change the resonant frequency and impedance bandwidth drastically [23] under wet condition. According to the consideration fact, the antenna needs to be designed to operate well in all conditions. The antenna performance of resonant frequency, reflection coefficient and bandwidth are evaluated under both conditions.

3.1. Antenna Placement on Human Body

In practice, the textile antenna is usually placed on the arm, chest and backside of a human body. In this research, Gustav human body model (as shown in Fig. 2) that is made available by CST is used in the simulation. The antenna is placed at the backside of the human body with 1 mm gap. The backside area is chosen because at this position the frequency detuning of the antenna due to the composition of human body (skin, tissue and muscle) can be minimized [24]. In addition, the flat and wide body area is proposed as the suitable antenna placement as it avoids bending effect on curved body.

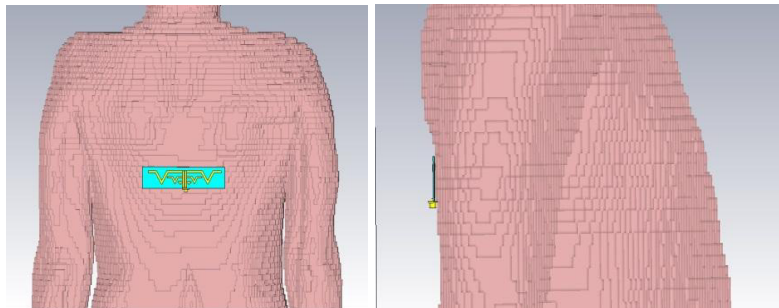


Figure 2. Body antenna placement.

In Figs. 3, 4 and 5, the resonant frequency is shifted due to the presence of human. The antenna placement on human body provides impact on antenna performance due to electromagnetic coupling effect of body tissue. For on-body measurement, the resonant frequency of 2.45 GHz band antenna is shifted for about 0.69 GHz as depicted in Table 1. The resonance of multiband antenna is shifted about 0.25 GHz at the first band, 1.26 GHz at second band and 1.83 GHz at the third band to the lower frequency. The operating frequency of ultra wideband antenna is slightly affected. However, the ultra wideband antenna will not operate between 5.12 and 6.14 GHz with presence of the human body. The impedance bandwidth has slightly increased by the proximity to the human body due to the influence of body on the reactive field.

3.2. Bending Effect

While the textile antenna provides potential solution for body centric communication, it has some drawback due to bending. To account for the bending effect, the textile antenna is bent on cylindrical polystyrene ($\epsilon_r \approx 1$) with diameter of 7 cm which is equivalent to the size of the human arm. Fig. 6 shows the bending experiment of the multi-band fractal Koch dipole textile antenna by using polystyrene

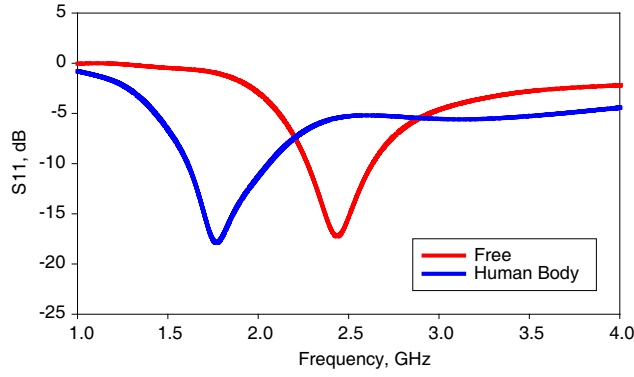


Figure 3. Simulated reflection coefficient $|S_{11}|$ plot of 2.45 GHz dipole antenna with human body.

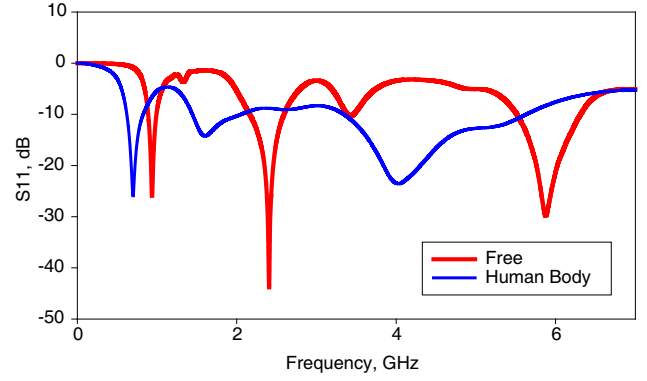


Figure 4. Simulated reflection coefficient $|S_{11}|$ plot of Koch-fractal multiband antenna with human.

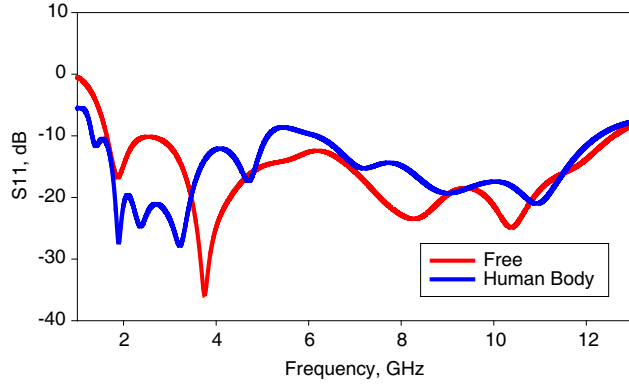


Figure 5. Simulated reflection coefficient $|S_{11}|$ plot of CPW-fed ultra wideband antenna with human body.



Figure 6. Koch fractal multiband antenna are bent on polystyrene cylinder.

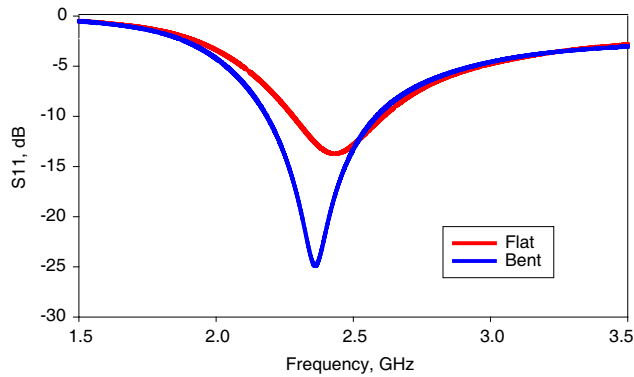


Figure 7. Measured $|S_{11}|$ plots of the 2.45 GHz single band antenna under bent condition.

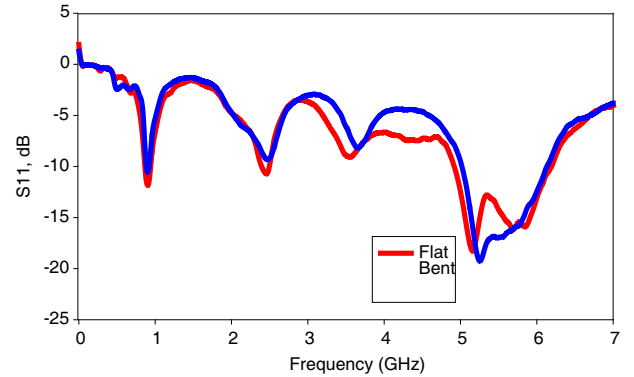


Figure 8. Measured $|S_{11}|$ plots of the Koch fractal multiband antenna under bent condition.

cylinder. The measured results of the planar antennas under free and bent condition are plotted in Figs. 7, 8 and 9 respectively. Moreover, the results obtained are tabulated in Table 1. As can be seen, no significant changes of the $|S_{11}|$ when the antennas are bent. Although, slight resonant frequency detuning is observed for each frequency band of all type of planar antennas investigated in this paper, the performance of the antenna is acceptable fullfill the requirement application.

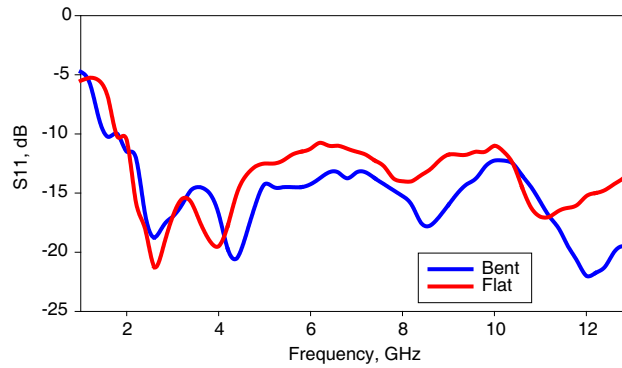


Figure 9. Measured $|S_{11}|$ plots of the CPW fed ultra wideband antenna under bent condition.

Table 1. Resonance frequency and bandwidth of planar antennas with human body.

Types of antenna	No of Band	Resonance Frequency (GHz)		Bandwidth (GHz)	
		Free	Human Body	Free	Human Body
Single Band	1st	2.45	1.76	0.36	0.44
Multiband	1st	0.94	0.69	0.10	0.25
	2nd	2.41	1.15	0.42	0.61
	3rd	5.88	4.05	0.79	2.35
Ultra wideband	1st	1.64–12.60	1.32–5.12, 6.14–12.27	10.96	9.93

Table 2. Resonance frequency and bandwidth of planar antennas under bent condition.

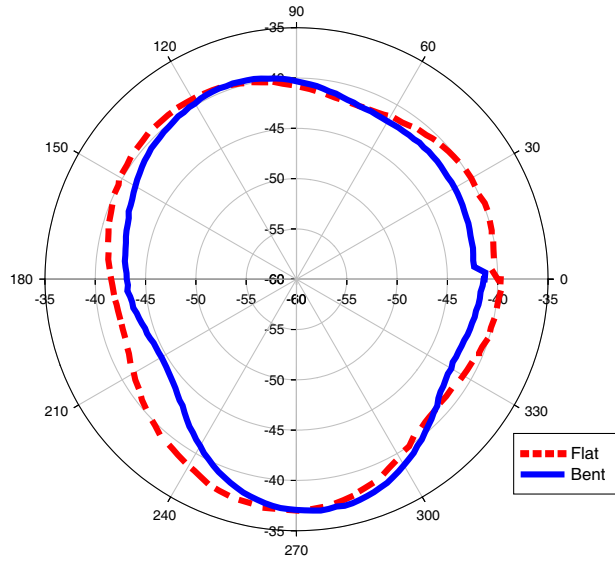
Types of antenna	No of Band	Resonance Frequency (GHz)		Bandwidth (GHz)	
		Flat	Bent	Flat	Bent
Single Band	1st	2.44	2.35	0.32	0.42
Multiband	1st	0.915	0.915	0.11	0.09
	2nd	2.44	2.48	0.15	-
	3rd	5.11	5.16	1.05	1.00
Ultra wideband	1st	1.8–13.0	1.8–13.0	11.2	11.2

In this study the effect of antenna bending has been analyzed. Table 2 shows the effect of bending for three different types of antennas. Based on Table 2, the resonant frequency is shifted slightly to lower frequency under bent condition primarily for 2.45 GHz single band antenna about 0.09 GHz and multiband antenna at the third band about 0.05 GHz. It can be seen that only minor shift on the resonant frequency is observed when the antenna is bent if compared to the flat condition. The input impedance and resonant frequency are slightly changed due to stretching and compression of antenna structure, hence altering the resonant length of the antenna. On the other hand, bending has negligible effect on the ultra-wideband antenna performance. The antenna structure maintain the antenna performance under bent condition. Despite slight deviation are existed compared to the flat condition, the bent CPW monopole could maintained a 10 dB bandwidth, hence preserving the wideband feature of the antenna. Generally, bending is found to cause minor effect on the impedance matching of the antennas.

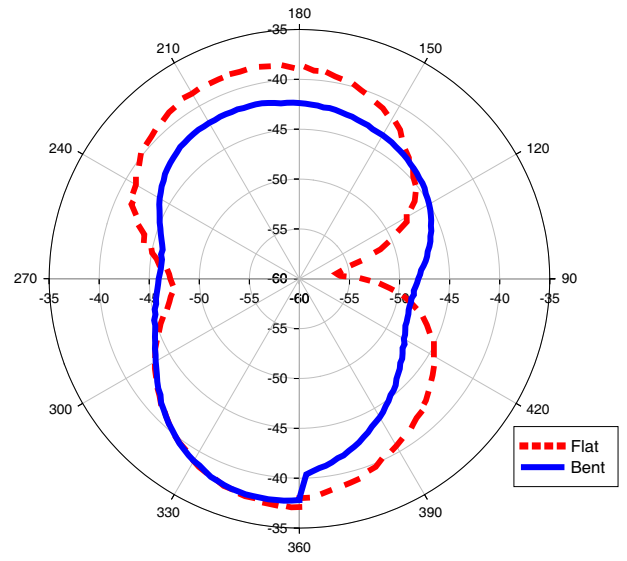
The radiation patterns for the fractal Koch multiband are shown in Fig. 10. Fig. 11 shows the 2.45 GHz dipole antenna with bending radius using cylindrical polystyrene. The simulated and measured

radiation pattern shows a good agreement, generating a near omnidirectional pattern in azimuth plane. The same result is obtained for single band textile dipole antenna. The antennas produce omnidirectional radiation pattern at straight and bent condition as shown in Fig. 12. The insignificant discrepancy has proved that the antennas are less affected by the bending size. From the graph, the textile CPW monopole retained good performance under bending condition. However, small deviation is observed between the bent and flat antennas.

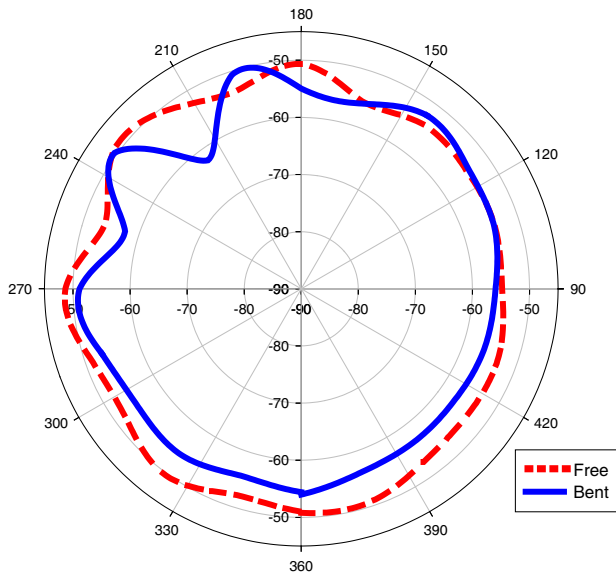
Figure 13 shows the measured radiation patterns for UWB antenna under bent and flat conditions at 2.45 GHz and 5.8 GHz, respectively. The polar plots show that the radiation pattern characteristics are found to be reasonably retained between bent and flat cases at 2.45 GHz and 5.8 GHz for both planes. From the results, small deviations can be observed especially in the E plane's patterns. However, since the deviation is minor, satisfactory agreement between the patterns of bent and flat monopoles is concluded.



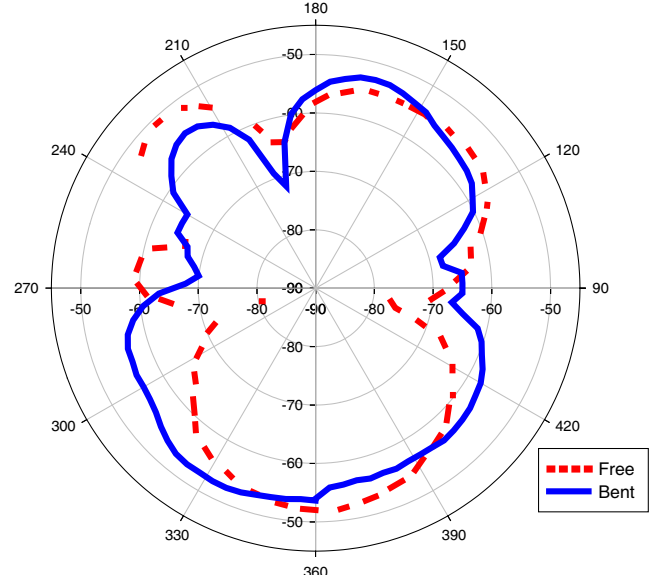
(a) E plane --- 0.915 GHz



(b) H plane --- 0.915 GHz



(c) E plane --- 2.45 GHz



(d) H plane --- 2.45 GHz

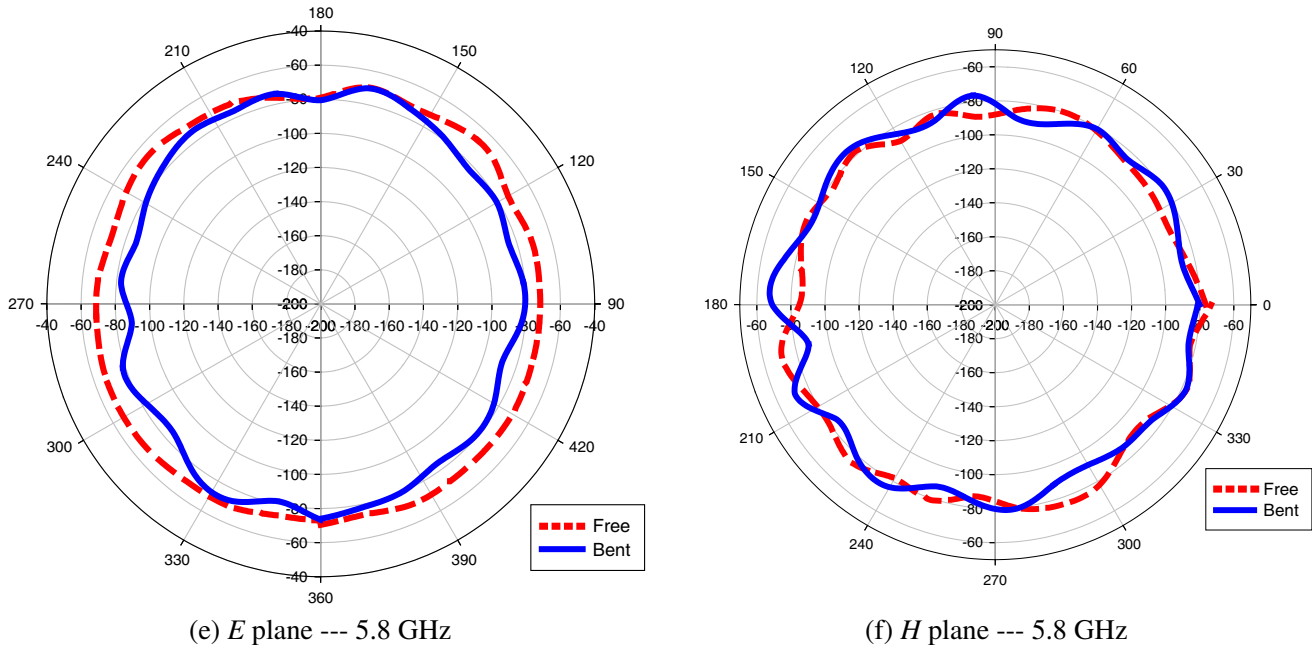


Figure 10. Measured radiation patterns of multiband antenna at 0.915, 2.45 and 5.8 GHz under bending condition.



Figure 11. Bending experiments of fully textile dipole antenna.

3.3. Wet Conditions

In wearable communications systems, wet conditions are also needed to be considered. If the antenna used is a textile type of antenna, it is specifically designed to be able to function in wet environment such as in rain or during washing process. In order to test the performance of the wearable antenna in wetness conditions, it is fully immersed in water.

The actual mass of the antenna as weighed by using digital scales before it is immersed into the water is shown in Fig. 14. After the antenna is completely immersed into the water, the weight is increased for almost 50% from actual weight. Then, the antenna is left to dry to monitor the percentage of water absorption reading, which is found to reach 100, 50 and 0%. Next, the antenna is soaked into the water, and the weight is then recorded. The $|S_{11}|$ of the antenna is collected continuously until the antenna is fully dried. The antenna is then dried under the sunlight to obtain variable weight of the antenna. These steps are repeated for all antennas considered in this work. The percentage of water absorption

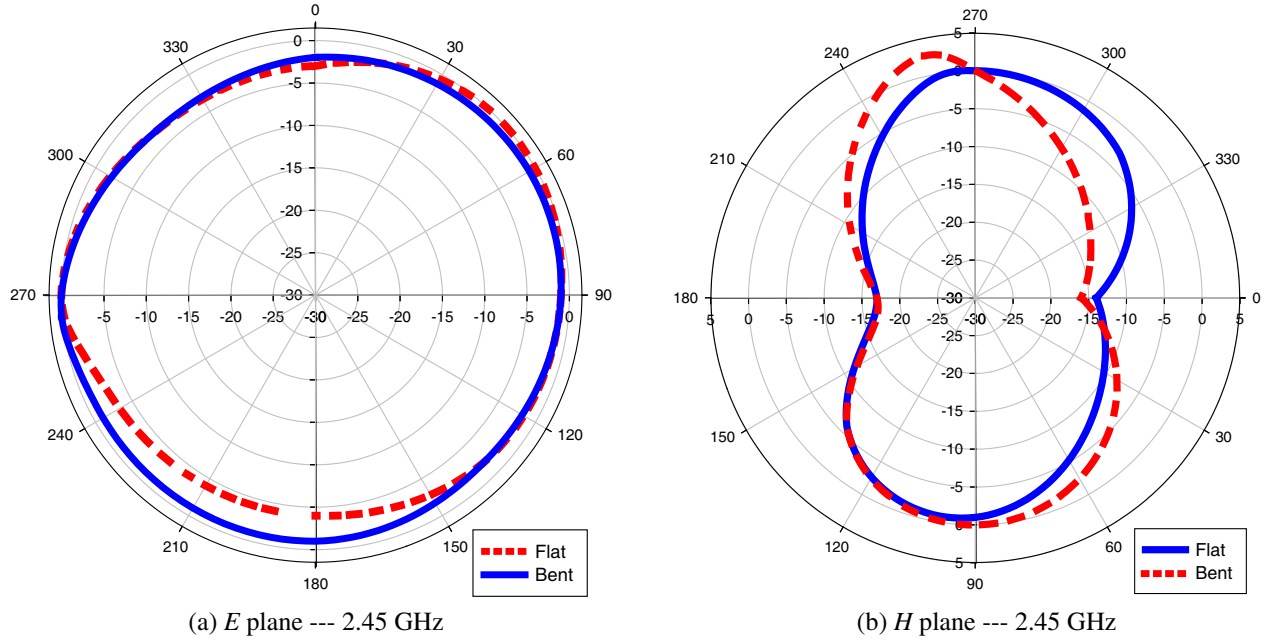


Figure 12. Measured radiation patterns of dipole antenna at 2.45 under bending condition.

Table 3. Resonance frequency of the antenna under wetness condition.

Types of antenna	No of Band	Resonant Frequency (GHz)			
		Before washing (0%)	Complete Wet (100%)	Damp (50%)	Dried (0%)
Single Band	1st	2.45	1.64	1.82	2.39
Multiband	1st	0.89	0.72	0.76	0.89
	2nd	2.45	1.20	1.78	2.50
	3rd	5.84	3.32	4.50	5.69
Ultra wideband	1st	1.77–13	3.18–13	1.99–13	1.80–13

can be calculated by using Equation (1) below:

$$\text{Water absorption}(\%) = \frac{\text{current mass} - \text{dry mass}}{\text{immersed mass} - \text{dry mass}} \times 100\% \quad (1)$$

From wetness experiments, the performances of the antennas are evaluated and tabulated in Table 3. From Fig. 16, the resonant frequency of 100% wet multiband antenna has dropped from 0.89 to 0.72 GHz, that is about 19% at the first band, 2.45 GHz to 1.2 GHz that is about 49% at the second band, and 5.84 to 3.32 GHz that is about 43% at the third band. However, the resonant of single band antenna is changed from 2.45 to 1.64 GHz, by about 33% as shown in Fig. 15. The starting operating frequency of ultra wideband antennas covers from 1.77 GHz before washing as shown in Fig. 17. However, the operating frequency is changed to 3.18 GHz after the antenna is fully wet. The resonant frequency of 100% fully dried comes back to the same value as the actual antenna in free space. It is observed that the antenna performance is degraded as the water absorption is high and then comes back to the usual performance when there is no more water absorption. The operating frequencies are shifted to the lower frequency implying that the effective dielectric constant is increased by the existence of water.

Figures 15, 16 and 17 show the reflection coefficient $|S_{11}|$ responses at different percentages of wetness level for textile antenna, respectively. The textile antenna is fully dried with 0% of water level

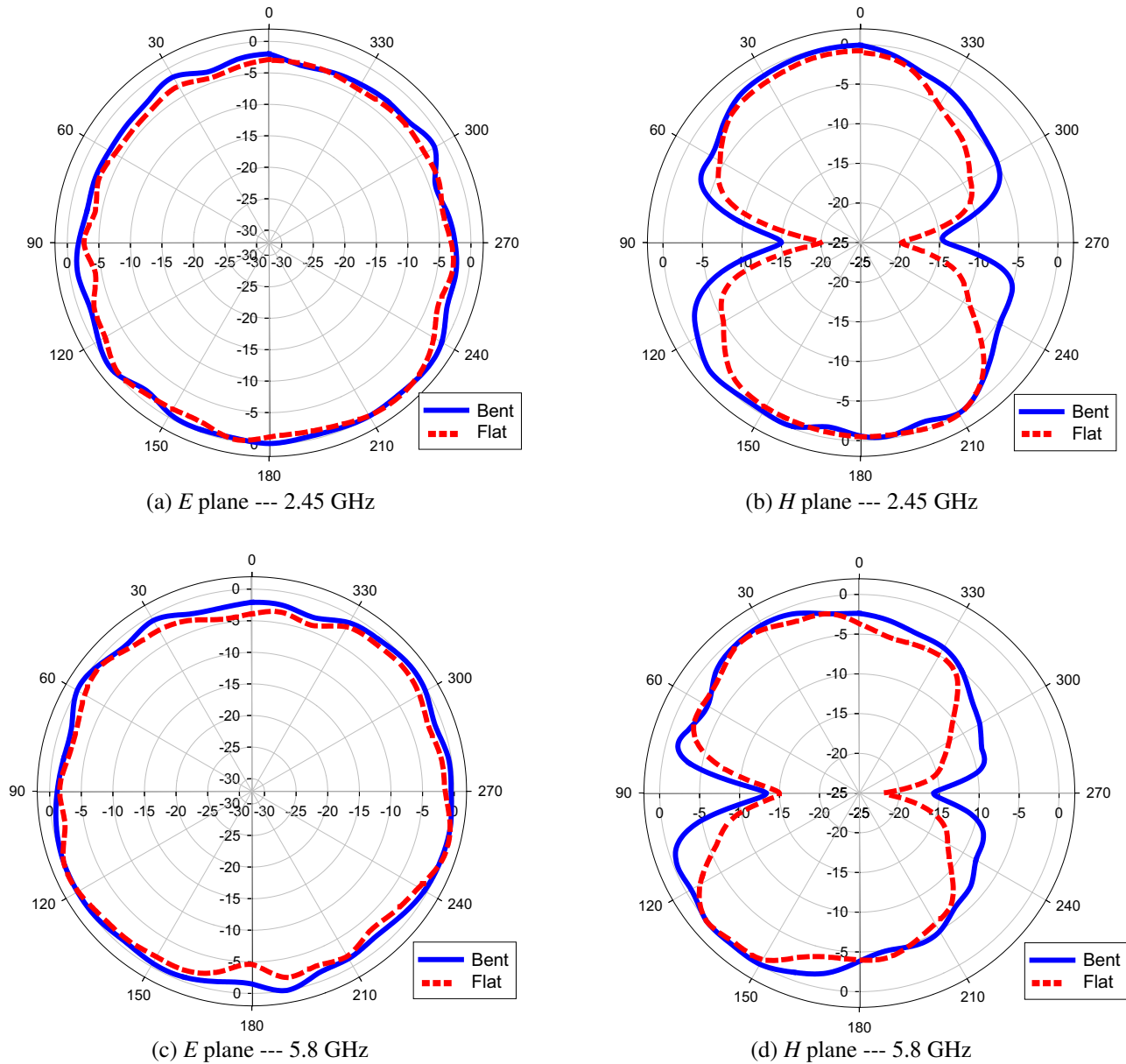


Figure 13. Measured radiation patterns of textile UWB antenna at 2.45 and 5.8 GHz under bending condition.

while the textile antenna is completely in wet condition with 100% of water level. Table 3 shows the measured resonant frequency result of the single band, multiband and UWB antenna in four different states such as before washing, complete wet, damp and dry. Figures 15, 16 and 17 show that the reflection coefficients in dB of the antennas are proportional to the wetness level percentage. In other words, the reflection coefficients of the antennas are shifted to the lower frequency region with increasing volume of water in the antennas. The presence of water changes the properties of the substrate. The water increases the permittivity of the substrate to a higher value which causes the minimum reflection coefficient to shift to lower frequencies. It can be concluded that single and multiband antennas cannot operate well in wet condition. However, the fully wet UWB antenna still performs well between 3.18 and 13 GHz.

Similar to previous case for the complete wet antenna, S_{11} performances of all the antennas deteriorate since high dielectric constant of water dominates the permittivity of the wet antenna.



Figure 14. Fractal Koch multiband antenna are immersed in water.

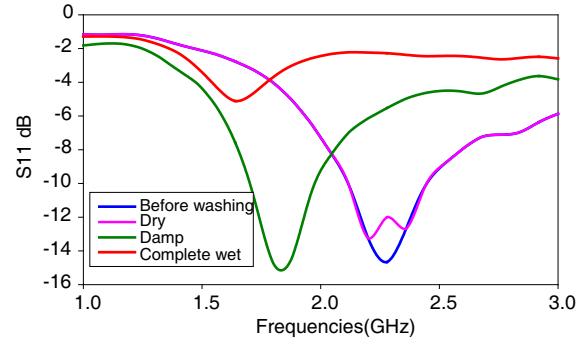


Figure 15. Measured $|S_{11}|$ plots of the 2.45 GHz single band antenna under wetness condition.

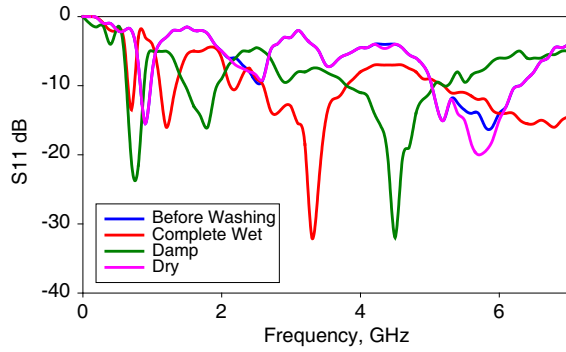


Figure 16. Measured $|S_{11}|$ plots of the Koch fractal multiband antenna under wetness condition.

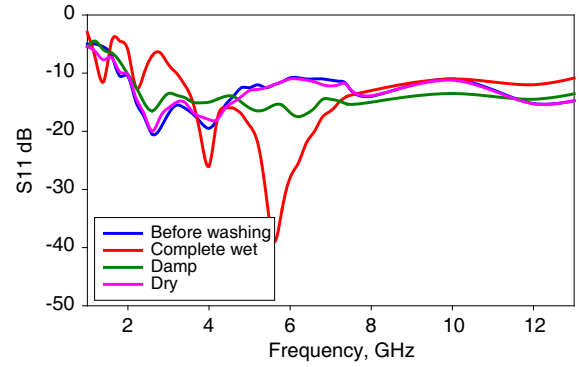


Figure 17. Measured $|S_{11}|$ plots of the CPW fed ultra wideband antenna under wetness condition.

Therefore, the resonance is seen to be shifted to the lower frequency as expected. The reflection coefficients of all antennas are observed and slowly return back to the original curve when the antenna is fully dried. However, since there is still moisture left in the antenna, the curve is not exactly the same as the original. On the other hand, the fully dried curve is seen to follow closely to the original before washing state. But, the exact original curve cannot be attained since the antenna experiences slight property changes due to shrinking.

4. CONCLUSION

Planar textile antenna is the most suitable antenna for body centric communication system. The textile antenna performance can be optimized by selecting materials with high conductivity and using a proper structure in the design. Additionally, the stability of antenna performance in terms of gain and operating frequency need to be considered for the used in various conditions such as on-body measurement, bending and wet condition. From the bending result, no significant frequency detuning is observed. To minimize the bending effect of an antenna, the antenna needs to have high bandwidth to ensure that the antenna is stable and can perform well at the desired operating frequency. The antenna also did not work under wet condition due to the high permittivity value of water. Therefore, the substrate needs to be made of waterproof fabric to ensure that the substrate has low water absorption. From the research, it can be seen that the CPW-fed ultra wideband antenna is the best candidate of planar textile antenna among Koch fractal multiband antenna and 2.45 GHz dipole antenna because the antenna performs well under all consideration including on-body measurement, bending effect and wetness condition.

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